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Applied Geochemistry xxx (2010) xxx–xxx

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Anomalous fluid emission of a deep borehole in a seismically active area of Northern Apennines (Italy)

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A B S T R A C T

The Miano borehole, 1047 m deep, is located close to the river Parma in the Northern Apennines, Italy. A measuring station has been installed to observe the discharge of fluids continuously since November 2004. The upwelling fluid of this artesian well is a mixture of thermal water and CH_4 as main components. In non-seismogenic areas, a relatively constant fluid emission would be expected, perhaps overlaid with long term variations from that kind of deep reservoir over time. However, the continuous record of the fluid emission, in particular the water discharge, the gas flow rate and the water temperature, show periods of stable values interrupted by anomalous periods of fluctuations in the recorded parameters. The anomalous variations of these parameters are of low amplitude in comparison to the total values but significant in their long-term trend. Meteorological influences of rain and barometric pressure were not detected in recorded data probably due to reservoir depth and relatively high reservoir overpressure. Influences due to the ambient temperature after the discharge were evaluated by statistical analysis. It is considered that recorded changes in fluid emission parameters can be interpreted as a mixing process of different fluid components at depth by variations in pore pressure as a result of seismogenic stress variation. Local seismicity was analyzed in comparison to the fluid physico-chemical data. The analysis supports the idea that an influence on fluid transport conditions due to geodynamic processes exist. Water temperature data show frequent anomalies probably connected with possible precursory phenomena of local seismic events.

1. Introduction

Fluids in the upper crust are strongly involved in geodynamic processes. Crustal fluids as natural strain sensors have been studied by Kümpel (1992), Woith et al. (2003) and Koizumi et al. (2004). Variations in several parameters, in particular water level, water temperature or Rn concentration have been detected in many geological environments with fluid emissions in springs, mofettes or wells, e.g. Roeloffs (1998), Igarashi et al. (1993), Wang et al. (2004) or Itaba and Koizumi (2007). Relationships to local earthquakes are a matter of study. Buntebarth and Chelidze (2005) observed microtemperature variations in deep groundwaters induced by seismic activity. In Southern Italy the monitoring of a 500 m well discharging thermal water and CH_4 evidenced gas flow and temperature variations induced by local earthquakes (Colangelo et al., 2005, 2007).

In the Northern Apennines a 1040 m deep well was monitored with the purpose of evidencing possible variations in physico-chemical parameters due to local tectonic/seismic activity.

2. Geological setting

The Northern Apennines are a fold and thrust belt originating from the convergence between the European and African plates. As a result of the convergence all the Northern Apennines and in particular the Parma province are subjected to vertical uplift (Argnani et al., 2003) horizontal and vertical movements are responsible for local seismicity characterized by frequent seismic events of small and moderate size magnitude. Focal solutions of the moderate seismicity affecting the Northern Apennines show

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0883-2927/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.apgeochem.2010.01.012

Table 1
List of all seismic events in the frame of latitude of 44.2–44.65 and a longitude of 9.85–10.25N, according the web catalogue of INGV.

Number	Latitude	Longitude	Foci in km	Magnitude	Year	Month	Day
1	44.451	9.895	8.4	3.4	2006	4	1
2	44.237	10.202	9.5	1.5	2006	4	2
3	44.241	10.183	10	1.3	2006	4	2
4	44.227	10.238	7.8	1.4	2006	4	2
5	44.243	10.243	10.1	1.2	2006	4	2
6	44.219	10.145	5	1.7	2006	4	2
7	44.248	10.178	9.5	2	2006	4	2
8	44.244	10.158	9.4	1.7	2006	4	3
9	44.543	9.96	10	1.6	2006	4	14
10	44.583	10.043	8.5	2.7	2006	4	17
11	44.579	10.051	10.7	2.5	2006	4	17
12	44.564	10.046	10	1.7	2006	4	17
13	44.306	10.246	11.1	1.2	2006	4	27
14	44.303	10.216	10.9	1.6	2006	4	28
15	44.599	10.082	5	1.9	2006	4	28
16	44.63	10.096	10	1.2	2006	4	28
17	44.569	10.036	6	1.6	2006	4	28
18	44.588	10.07	5	1.8	2006	4	28
19	44.596	10.055	3.2	2.2	2006	4	28
20	44.626	10.033	10	1.5	2006	4	28
21	44.595	10.063	5.7	2.1	2006	4	28
22	44.603	10.071	2.4	1.9	2006	4	28
23	44.628	10.084	8.8	2.7	2006	5	1
24	44.545	10.01	10	1.8	2006	5	1
25	44.574	10.042	7.7	1.7	2006	5	1
26	44.611	10.083	10	1.7	2006	5	1
27	44.601	10.067	6.2	2.5	2006	5	1
28	44.582	10.036	10	1.6	2006	5	1
29	44.623	10.03	10	1.3	2006	5	2
30	44.512	9.985	10	1.8	2006	5	4
31	44.592	10.04	10	1.5	2006	5	7
32	44.582	10.059	6.7	2.3	2006	5	10
33	44.279	10.069	8.1	0.9	2006	5	29
34	44.288	10.212	11	0.9	2006	6	7
35	44.476	10.012	5.9	2.6	2006	6	19
36	44.424	10.002	5.2	1.3	2006	6	24
37	44.474	10.011	10	1.7	2006	6	24
38	44.301	10.09	5	2.7	2006	7	6
39	44.518	10.086	25.7	1.8	2006	7	13
40	44.401	9.96	9.1	1.5	2006	7	14
41	44.389	9.951	16.8	2.7	2006	7	14
42	44.648	10.165	10	1.9	2006	7	15
43	44.634	10.212	10	2	2006	7	16
44	44.511	9.856	10	1.7	2006	7	16
45	44.24	10.012	10	2.1	2006	7	20
46	44.425	9.997	10	1.3	2006	8	6
47	44.231	10.056	5	3.1	2006	8	10
48	44.55	9.916	10	1.8	2006	9	2
49	44.604	10.238	32.7	2.2	2006	9	7
50	44.251	10.046	10	1.1	2006	9	22
51	44.253	10.121	10	0.8	2006	9	30
52	44.354	10.162	9.3	1.1	2006	10	15
53	44.55	10.052	10	1.8	2006	10	21
54	44.507	10.203	22.9	1.8	2006	12	15
55	44.616	10.028	5.3	2.3	2006	12	30
56	44.214	10.054	10	1.3	2007	2	4
57	44.466	9.855	10	2.7	2007	2	11
58	44.473	10.04	10	2.3	2007	2	24
59	44.529	10.178	10.1	2.3	2007	2	24
60	44.54	10.113	10	1.8	2007	2	24
61	44.539	10.06	6.8	2.4	2007	3	7
62	44.603	10.158	23.7	1.2	2007	3	14
63	44.646	10.12	10	1.9	2007	3	25
64	44.358	10.204	9.9	1.3	2007	4	30
65	44.355	9.984	10	1.3	2007	5	7
66	44.254	10.101	8.3	1.6	2007	5	24
67	44.269	9.933	10.2	1.6	2007	6	1
68	44.525	10.124	10	1.9	2007	6	2
69	44.318	10.204	10.4	2	2007	6	4
70	44.485	10.053	8.2	3	2007	6	22
71	44.476	10.075	21.5	2.3	2007	6	28
72	44.215	10.21	6.3	1.8	2007	8	4
73	44.218	10.219	6.4	1.9	2007	8	5
74	44.237	10.243	12.8	1.2	2007	8	8

Table 1 (*continued*)

Number	Latitude	Longitude	Foci in km	Magnitude	Year	Month	Day
75	44.601	10.233	10.5	1.8	2007	8	11
76	44.312	10.205	10.3	1.7	2007	8	15
77	44.272	9.89	10	1.2	2007	8	27
78	44.271	10.117	6.4	1.1	2007	10	6
79	44.497	10.233	24.9	1.5	2007	10	20
80	44.212	10.082	10	1.3	2007	11	6
81	44.364	10.15	10	2.6	2007	12	16
82	44.209	10.08	10.8	1.6	2007	12	21
83	44.479	10.213	25.7	2.3	2007	12	24
84	44.512	10.176	3.9	4.1	2007	12	28
85	44.475	10.217	25.9	2.5	2007	12	28
86	44.518	10.216	20	1.7	2007	12	28
87	44.615	10.246	28.6	2	2007	12	28
88	44.466	10.197	28.3	2.1	2007	12	29
89	44.484	10.23	23.2	2.3	2007	12	30
90	44.507	10.245	22.8	1.8	2007	12	30
91	44.484	10.212	24.4	3.1	2007	12	31
92	44.484	10.241	26.5	2.8	2007	12	31
93	44.506	10.248	24.9	1.7	2007	12	31
94	44.492	10.202	10.5	2.1	2008	1	1
95	44.499	10.244	22.9	2	2008	1	1
96	44.489	10.228	22.6	2.3	2008	1	9
97	44.503	10.235	23.9	1.4	2008	1	25
98	44.529	10.236	17.2	1.8	2008	1	26
99	44.536	10.127	10	2	2008	1	31
100	44.203	10.228	9.3	2.5	2008	1	31
101	44.226	10.126	10,6	1.7	2008	2	9
102	44.553	10.241	24.4	1.6	2008	2	10
103	44.531	10.231	22.3	1,6	2008	2	14
104	44.528	10.221	23.6	1.7	2008	2	14
105	44.524	10.169	9.5	2.1	2008	2	17
106	44.567	10.224	23.3	1.6	2008	2	18
107	44.51	10.234	22.7	2.6	2008	3	29
108	44.64	9.982	18.3	3.2	2008	4	3
109	44.299	10.034	10	1,8	2008	4	22

the occurrence of extensional faults trending NNW–SSE (Frepoli and Amato, 1997). Northern Apennines seismicity is mainly located within the upper 20 km, although some events deeper than 50 km have been recorded (Selvaggi and Amato, 1992). In the period 1907–1911 a well for hydrocarbon research was drilled close to the locality of Miano, in the Municipality of Corniglio, Parma province, Northern Apennines. The so called Miano well is located on an overthrust basement (Boccaletti et al., 2004), which is seismically active. Main tectonic units recognizable in the area are the Caio unit, the Canetolo unit, the Falda Toscana unit, the Monte Piano unit and the Sporno unit. The Caio unit is of Cretaceous age and is composed of calcareous sandstones. The Canetolo unit is composed of carbonatic and argillic sandstones of Cretaceous age. The Falda Toscana unit is composed of sandstones of the Macigno formation. The Monte Piano unit is composed of sandstones and marls while the Sporno unit is constituted of carbonatic sandstones.

The following rocks were encountered during drilling:

- interval 0–585 m sandstones with clays of the Canetolo unit;
- interval 585–660 m carbonatic sandstones with clays of the Canetolo unit;
- interval 660–850 m marls with sandstones of the Marra marls formation;
- interval 850–1047 m sandstones with clays of the Pracchiola sandstones formation.

During drilling, gas emissions were encountered in all geologic formations; traces of oil were encountered at depths of 580, 790 and 850 m. Brackish water eruptions were noticed at depths of 929, 977 and 985 m (Geogas srl., 1995).

After drilling, the well produced a mix of warm brackish water (39 °C) and CH_4. Methane was utilized in the period 1936–1957 after separation from water. In the period 1958–1990 warm water was utilized for thermal baths but at the present time all equipment has been abandoned. Methane gas pressure is 0.3–0.5 kg/cm^2 while water flow rate is 1 L/s.

3. Seismicity

The Northern Apennines are a seismically active region of the Mediterranean area. Geodynamic processes induce strain and stress variations and, in principle, can affect rock pore pressure values. Local seismicity is characterized typically by events characterized by $M < 3$. All seismic events within a radius of approximately 12 km from the well have been selected. Correlation tests with events located at larger distances showed no effect on fluid emission variations. The frame is bounded by coordinates of 44.2–44.65N and 9.85–10.25E. Table 1 shows these events in the period 1/2006–4/2008. Running numbers indicate local seismicity in Figs. 8–10.

4. Fluid characterization and genesis

The Miano well water is characterized by a total salinity of 4.48 g/L and is of Na–Cl-type (Francavilla et al., 1982). The $^{18}O/^{16}O$ ratio was −8.46 ($\delta D = -58$) on July 10, 2004; −8.1($\delta D = -56$) on March 15, 2005; and −8.64 ($\delta D = -58$) on May 22, 2005.

Recent sampling has evidenced the absence of ^3H (T.U. = 0.5 ± 0.4) indicating a residence time >50 a. Thus the Miano

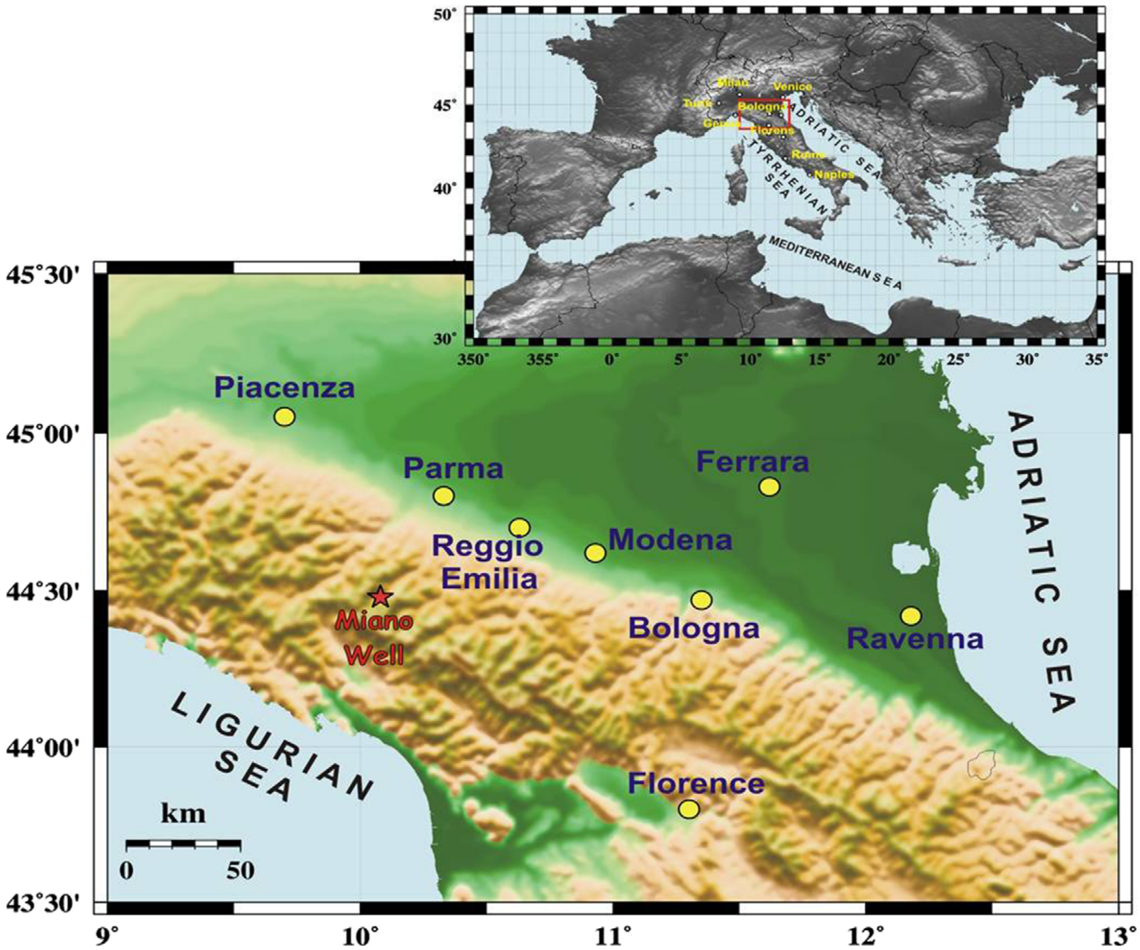

Fig. 1. Location of the Miano well (red star) in the Northern Apennine belt. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Chemical and isotopic composition of the fluids vented at the Miano well.

Sample	Date	He	O_2	N_2	CH_4	CO_2	R/R_a	He/Ne	δ^{13}_{C1}	δD_{C1}
Gas phase										
Miano[a]	n.a.	n.d.	1.07	4.75	93.35	0.71	n.d.	n.d.	n.d.	n.d.
Miano	07/10/2004	3.8E−05	0.02	0.81	98.78	0.39	0.01	184.93	n.d.	n.d.
Miano	22/03/2005	1.7E−05	0.60	1.57	97.21	0.62	n.d.	n.d.	n.d.	n.d.
Miano[b]	14/11/2005	1.9E−05	0.03	0.91	98.62	0.44	n.d.	n.d.	−39.38	−168.40

Date	T°C	pH	cond mS	Li	Na	K	Mg	Ca	F	Cl	Br	SO4	HCO_3	TDS	$d^{18}O$	dD
Liquid phase																
7-ott-04	39	7.6	6.81	0.10	66.92	0.51	0.59	2.20	0.22	63.74	0.020	0.14	4.6	138.9	n.d	n.d
10-lug-04	n.d.	n.d.	n.d.	n.d	67.85	0.57	0.65	2.33	0.24	63.42	0.013	n.d	5.4	140.4	−8.46	−58
15-mar-05	n.d.	n.d.	n.d.	0.07	64.05	0.55	0.59	2.41	0.24	63.45	0.098	n.d	5.4	136.7	n.d	n.d
22-mag-05	n.d.	n.d.	n.d.	0.09	69.37	0.56	0.69	2.76	0.22	66.2	n.d	0.27	5.4	145.4	n.d	n.d
06/04/2006	n.d.	n.d.	n.d.	n.d	64.13	0.60	0.55	2.14	0.22	62.17	0.000	0.04	4.5	67.4	n.d	n.d
06/02/2008	39	7.95	n.d.	0.12	63.26	0.58	0.54	2.81	0.23	62.24	0.000	0.05	5.2	67.3	n.d	n.d

Q2 The analytical results are expressed as volume% for the gas phase and as meq/L for the dissolved ions. n.a. = not available; n.d. = not determined; [a] = after Duchi et al., 2005; [b] = after Etiope et al., 2007.

hydrologic circuit is fed by meteoric waters enriched in salts possibly from evaporitic layers. Since no significant evaporitic layers were reported during drilling it is more probable that meteoric waters mix at depth with small amounts of fossil hypersaline water linked to hydrocarbon reservoirs. Hypersaline fossil waters have been found in many deep hydrocarbon wells of the Northern Apennines and the Po valley. Thus the sensitivity to seismic events of the Miano well can be attributed to the size of the deep hydrologic circuit, to the semiconfined condition of the reservoir and to mixing with a deep non meteoric water component.

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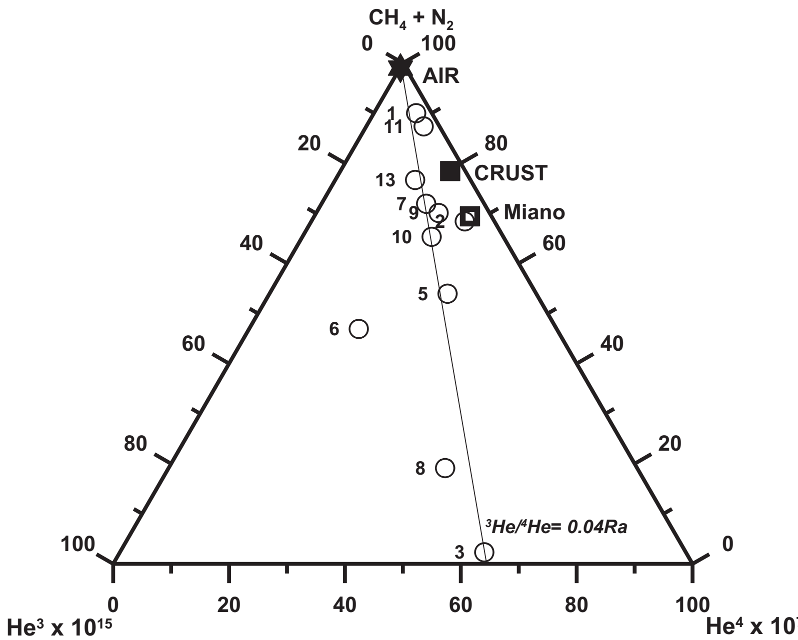

Fig. 2. ^3He–^4He–$CH_4 + N_2$ triangular plot: CH_4 and N_2 are plotted together as they represent the typical gas species in crustal-hydrocarbon environments. The compositions of air and a crustal, CO_2-dominated gas, are reported. The plotted composition accounts for gases from mud volcanoes and wells of the Northern Apennines. Numbers indicating the sampling site are from Table 2.

Fig. 3a. The Miano station with the gas/water separator on the left site, the tube to the house and the drum gas counter on the right site.

The features mentioned indicate those of a gas phase that are of deep origin and released because of vertical migration of the buried hydrocarbons (Borgia et al., 1988). Hydrocarbon generation and accumulation are the result of Neogene tectonics with Apennines orogenesis. Most of the gas released in the investigated area is biogenic, characterized by negative values of the isotopic composition of CH_4 (C1): $-76 < \delta^{13}C < -60$; $-223 < \delta D < -171$, and generally stored in Plio- to Pleistocene sediments. A minor amount of gas is thermogenic (CH_4 isotopic composition in the range of $-50 < \delta^{13}C < -30$; $-215 < \delta D < -153$) and normally found in pre-Pliocene reservoirs (Novelli and Mattavelli, 1988) (see Fig. 1). Q1

The gas phase released from the well of Miano is CH_4-dominated with minor amounts of N_2, CO_2 and He. Oxygen is detectable only in negligible concentrations (see Table 2). The chemical composition clearly shows that the gas derives from

Fig. 3b. The water outlet at the house with the water temperature probe and the water flow sensor.

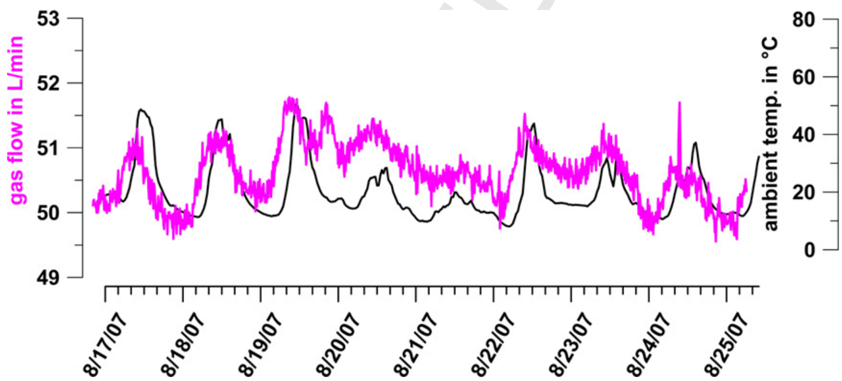

Fig. 4. Gas flow record compared to daily ambient temperature. Gas flow oscillations are limited when ambient temperature excursion is low.

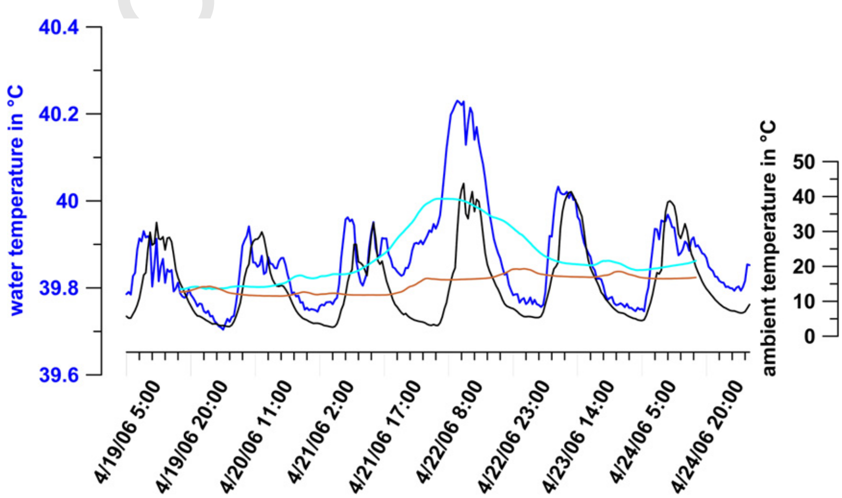

Fig. 5. Records of water temperature (blue) and ambient temperature (black) show typical daily variations except on April 21/22, when water temperature increased during the night and following day. The 24-h running average displays this anomaly as a significant increase in water temperature (light blue) and a relative constant ambient temperature (brown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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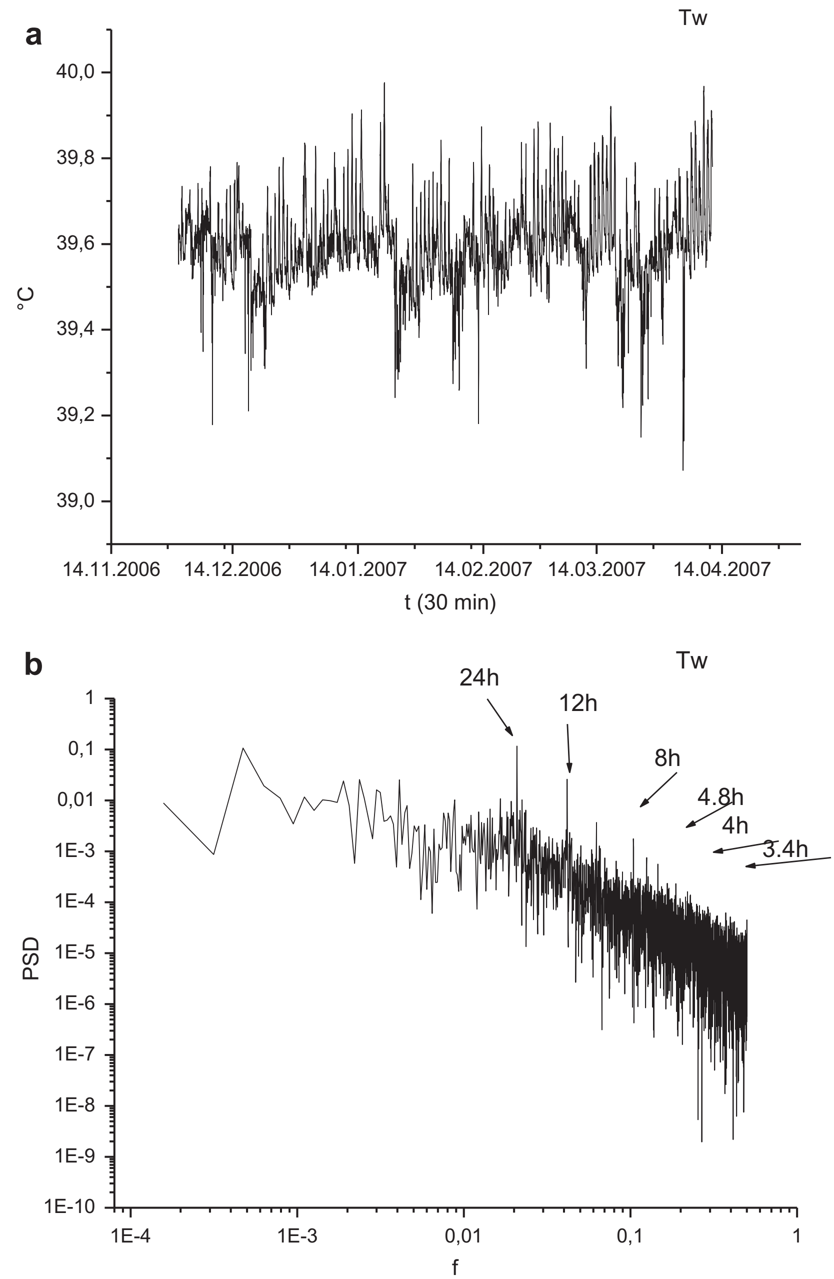

Fig. 6. a–h: Example of the recorded data sets of water and ambient temperature in the period of November 2006–April 2007. The power spectra (b and e) were calculated from the original data of water temperature T_w (a) and ambient temperature T_a (d). The final residual data $T_{w\text{-res}}$ (c) and $T_{a\text{-res}}$ (f) display time series after the removal of periodicities. The regression function of both $T_{w\text{-res}}$ and $T_{a\text{-res}}$ is used to calculate the difference between the recorded $T_{w\text{-res}}$ and the calculated $T_{w\text{-res}}$ from the ambient temperature. In that way the daily influence of the ambient temperature is reduced in the residuals. The result (h) is a time series of the final $T_{w\text{-residual}}$ without ambient influence. An anomaly indication is possible by calculation of a threshold, for example the 2σ value. The 95% confidence threshold (2σ) can separate anomalous high temperature data from “normal” variations. Periods with final residual values higher than the 2σ value will be therefore considered as anomalous in comparison to all other data.

the hydrocarbon reservoirs of the Northern Apennine, while the CH_4 isotopic composition (δ^{13}C and δD) (Table 2) displays a possible thermogenic origin. The ^{3}He–^{4}He–CH_4 + N_2 triangular plot of Fig. 2 provides information on both the composition and the origin of the released gases. The gas phase of Miano is reported in Table 2 compared to other CH_4-dominated gases from dry vents and mud volcanoes in the same area of the Apennine chain (Tosco–Emiliano Apennine). A typical crustal gas (CO_2-dominated) and air are plotted on the graph for reference. The advantage of such a triangular plot is that binary mixing relationships can be easily recognized by linear trajectories. Almost all the samples fall on a binary mixing line between air and a crustal end-member marked by a He isotopic ratio of 0.04 R_a that clearly represents the isotopic signature of the whole Northern sector of the Apennine chain. The gases from Miano show a further enrichment in crustal-type fluids: besides a similar content of CH_4 and N_2 the Miano gas phase has higher He content and a lower He isotopic ratio (0.01 R_a) compared to the other gases. This evidence can be interpreted as a consequence of

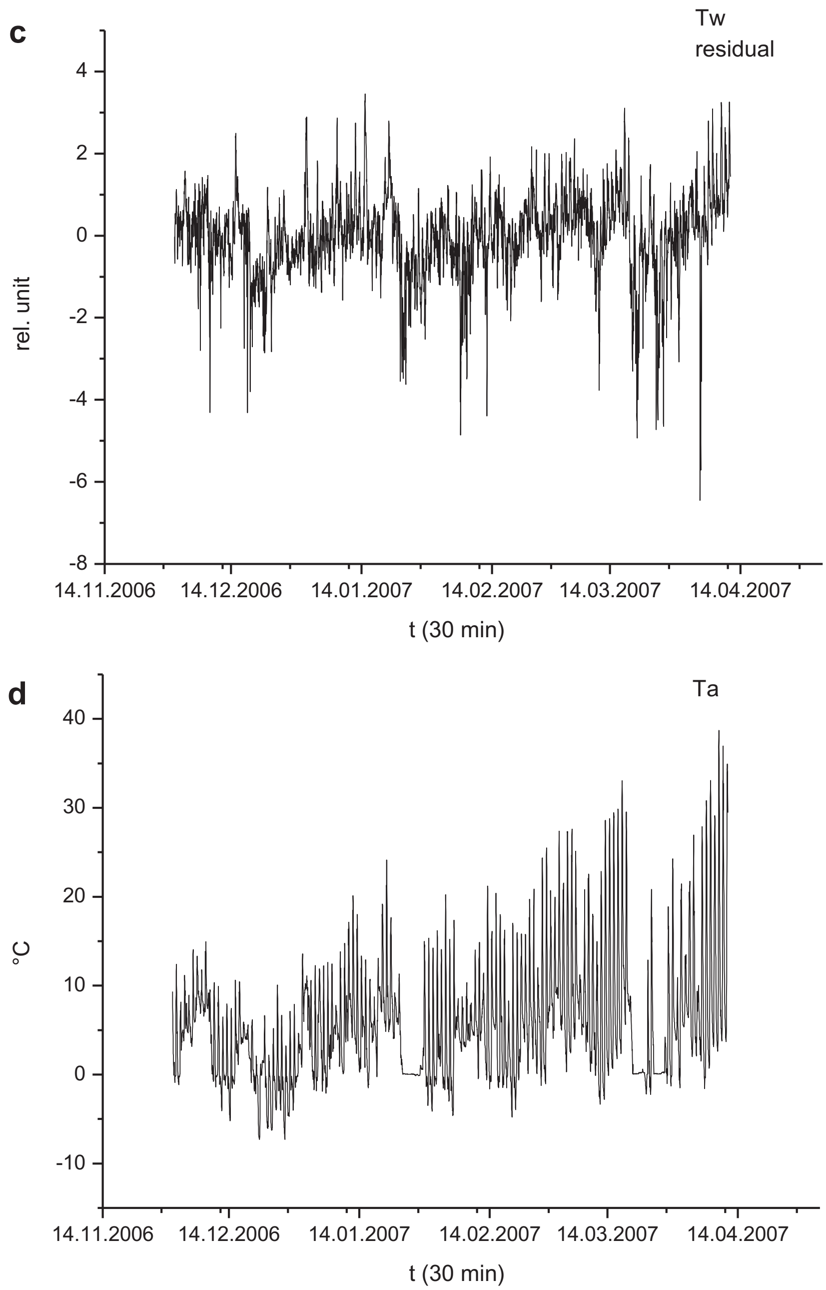

Fig. 6 (*continued*)

(1) a deeper origin of the Miano gases or;
(2) the presence of a deep-originating component mixed with the hydrocarbon gas mixture.

5. Technical properties of the station and their recorded parameters

The Miano borehole was drilled for oil and gas exploration in 1911. The depth of around 1000 m was extraordinary for that region in that time. The temperature of thermal water of around 39 °C gives indications of a slight local geothermal anomaly. Artesian flowing water enters the gas/water separator. The separated gas and water phases flow through plastic pipes of a few centimetres diameter to a house where the sensors for gas- and water flow and water temperature are installed. Figs. 3a and 3b show the location. The distance between the separator and the house is about 5 m.

A drum gas counter (Ritter) registered gas flow (Fig. 3a) continuously. Water flow was measured by a through flow turbine (Bürkert) in the range of mL/s.

The data from all probes were stored by means of two 16 bit data loggers, including the temperature of the data logger system (ambient temperature) and the battery voltage. The recording interval for the gas and water discharge was 10 min while the recording interval for temperature was 30 min. Long term recording periods are important constrains for reliable data interpretation.

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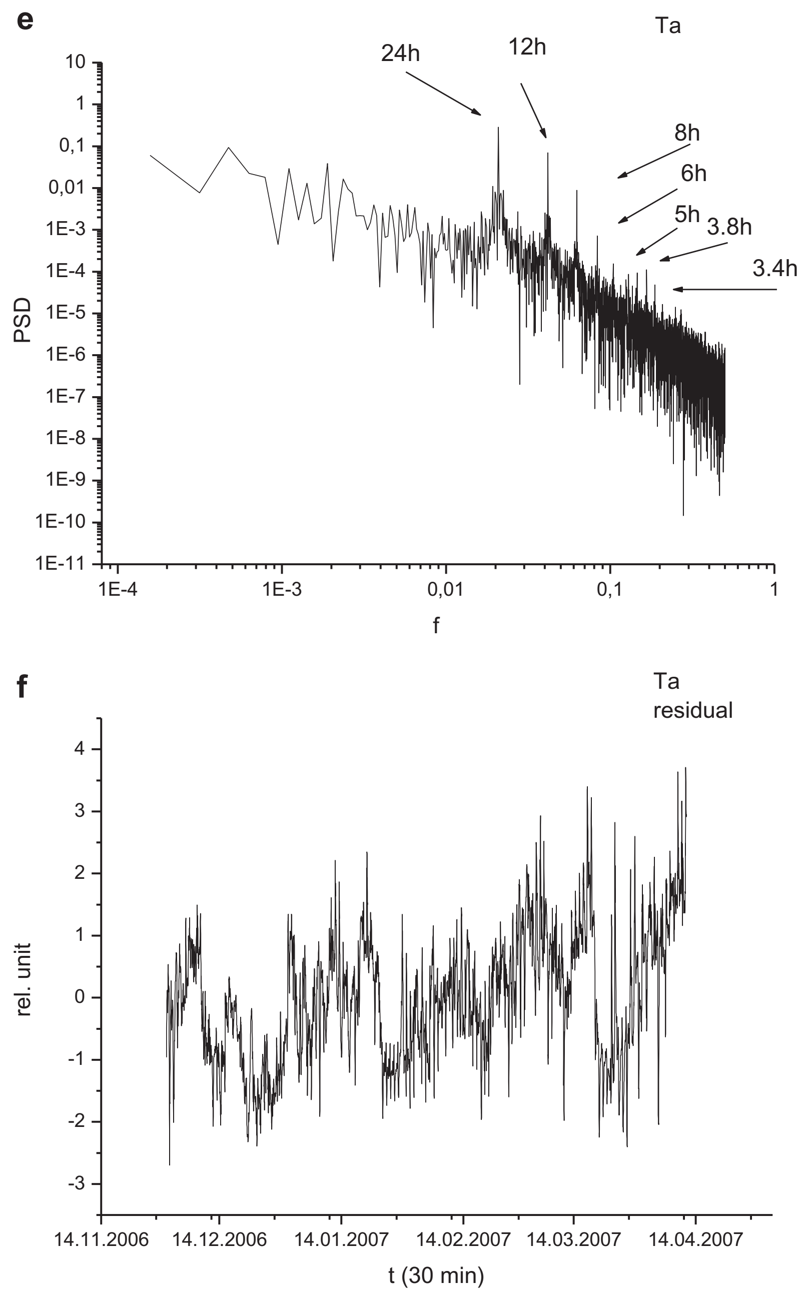

Fig. 6 (*continued*)

6. Variations of the recorded parameter

6.1. The gas flow data

Gas flow data show daily oscillations strongly correlated with the ambient temperature. Fig. 4 shows this effect in a detailed record during August 2007. Normal fluctuations are in the range of ±3% of the average value. Anomalous periods can be well recognized by simultaneous comparison with ambient temperature data.

6.2. The water flow data

Water flow through the pipe with a diameter of 6 cm is relatively constant. Frequent fluctuations are generated by the separation process of gas and water bubbles. Flow rate data were recorded every minute and stored as average value of a 10 min recording period.

6.3. The water temperature data

Water temperature data are probably the most informative. Data show a daily variation of water temperature. During the transport of thermal water through the pipeline to the house, water temperature was slightly influenced by typical day and night effects induced by direct sunshine on the pipe (heating effects) or rain/snow events (cooling effects). These influences can be identified by comparison with the simultaneous record of the ambient temperature. Therefore, a further temperature sensor was installed close to the pipe on the

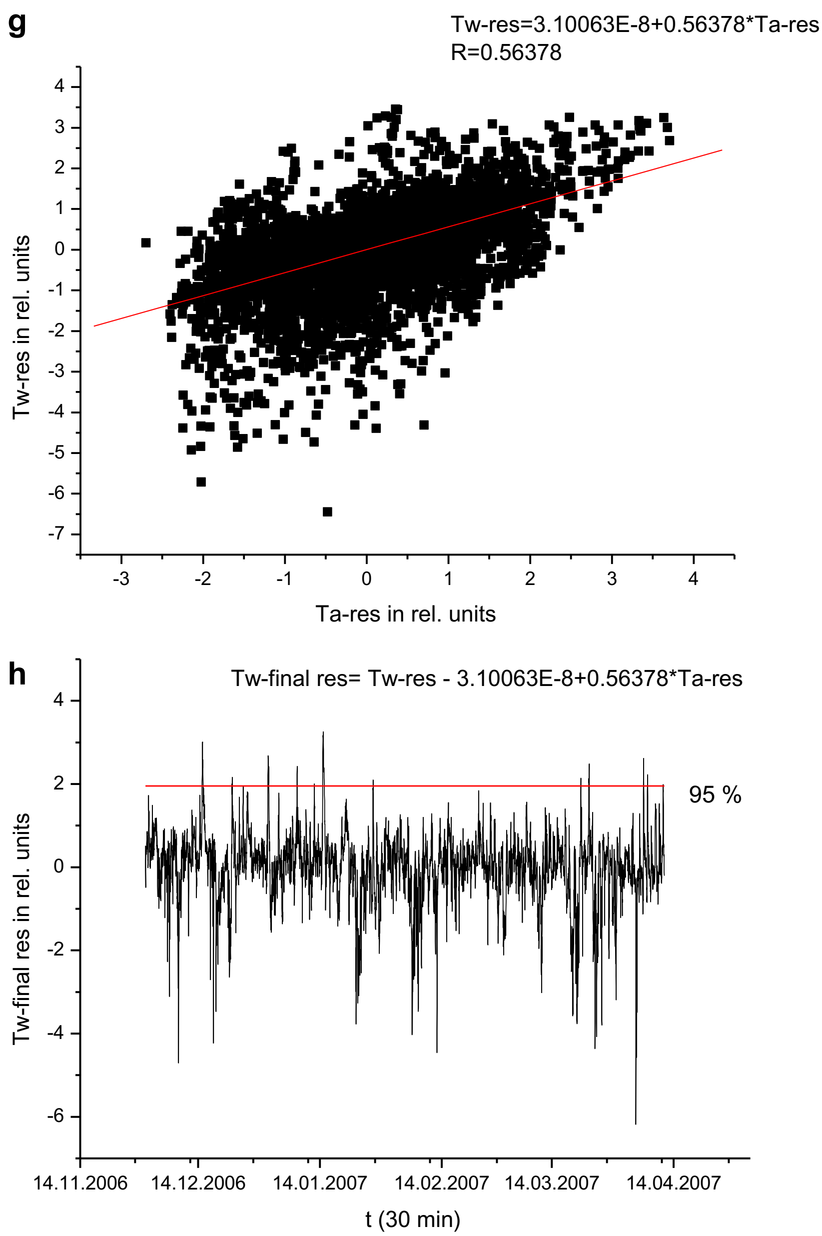

Fig. 6 (*continued*)

roof of the house to get optimal information about the daily variations of the ambient temperature from April 2006.

The two temperature probes of Pt100 sensors have an accuracy ±0.2 K and temporal stability of 0.06%. Normal periodic fluctuations of the two probes can vary in 24 h due to the effects of environmental conditions: 0.5 K for the thermal water and up to 50 K for the temperature on the roof of the house. The limited daily excursion of water temperature allows assumption of temperature as a constant parameter except during possible anomalous periods. The occurrence of an anomalous period can be detected by divergent behaviour in temporal variation of temperatures during the night (e.g. an increase of water temperature during the cooling night) and/or by an increased water temperature during the day in comparison to normal daily ambient variation. In both cases only positive anomalies can be recognized (Fig. 5). Rain events or snow which induce a short term negative anomaly due to a cooling effect on the water pipe can be identified.

A 24-h running average was calculated for both temperatures. In this way the daily effect can be easily reduced and strong anomalies are detectable as an increase in water temperature above the long term average (Fig. 5). To improve the reliability of the anomaly identification a further statistical evaluation was carried out.

7. Statistical evaluation of data

In order to remove both meteo-climatic effects and influence of the ambient temperature from water temperature data, a statistical procedure was applied, mainly based on evaluation of the power spectral density (PSD) of the signals (Currenti et al., 2005; Telesca et al., 2005). Fig. 6b and e shows PSD in water and ambient temperatures, respectively. Several cyclic

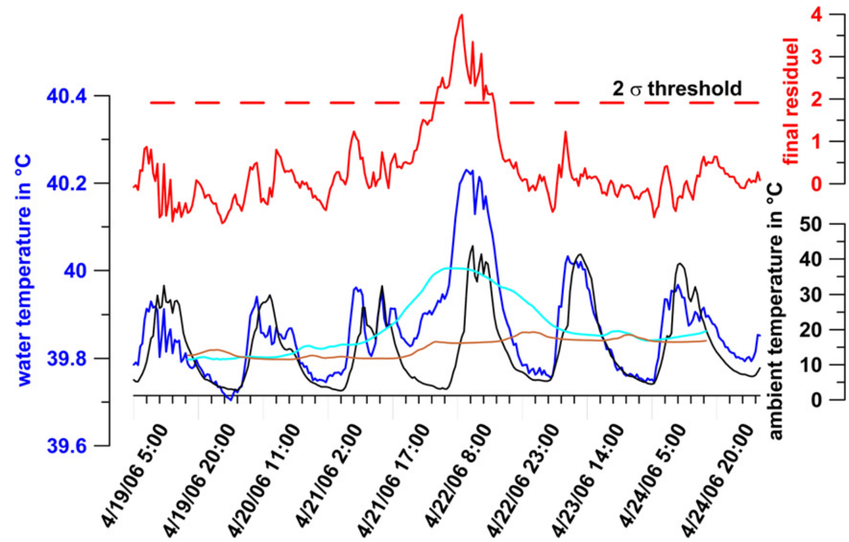

Fig. 7. Example of data evaluation by running average method (Fig. 5) and statistical analysis of residuals. The residual values (red line) above the 2σ threshold indicate an anomalous water temperature increase over 1 day. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

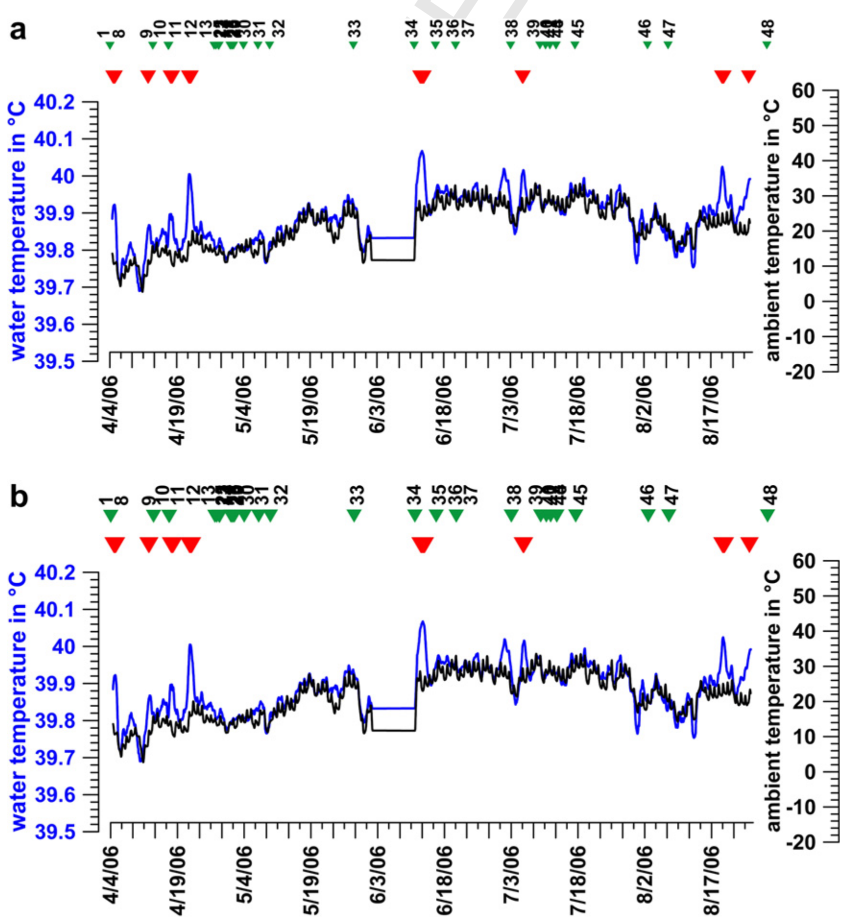

Fig. 8. Part one of the original data of water temperature (blue), ambient temperature (black) (above) and the result of the statistical anomaly evaluation (below). The running average values (blue and black) and the anomalous residuals (>2σ as red triangles) are presented for the period April–August 2006. A short technical data gap (storage overflow) in June is visible as a straight data line. The numbers of seismic events are according to Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

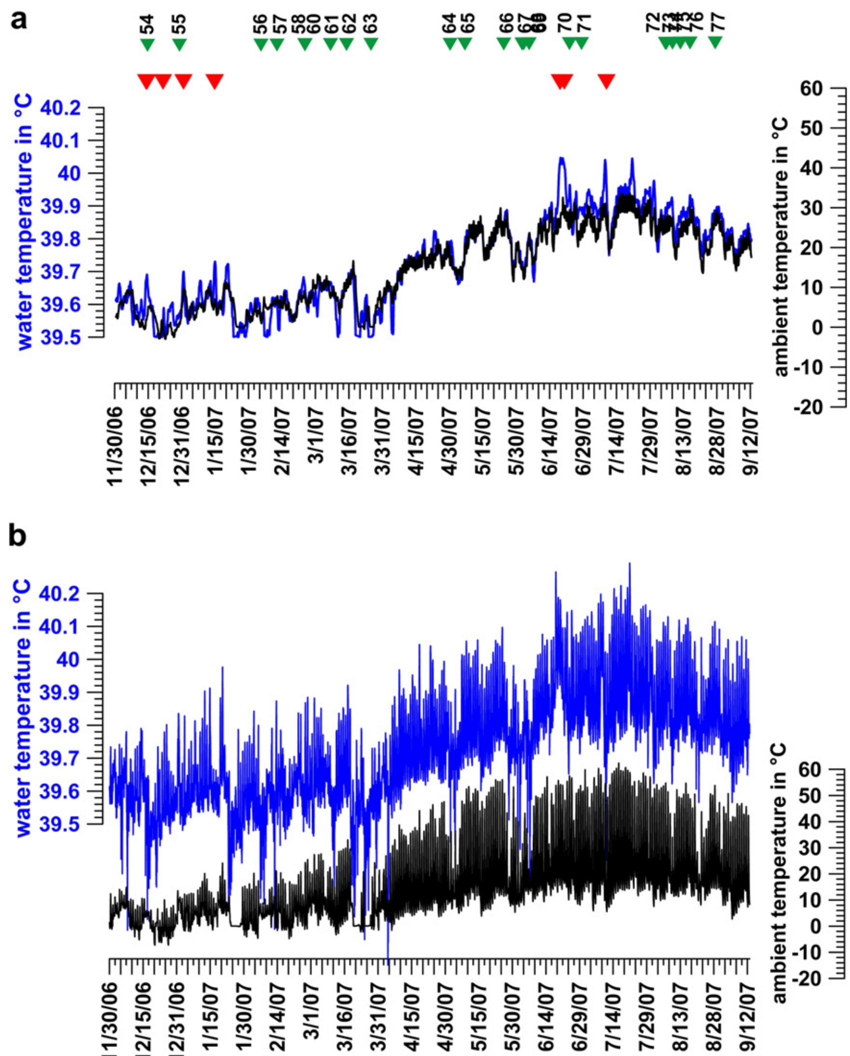

Fig. 9. Part two of original data of water temperature (blue), ambient temperature (black) and the result of the statistical anomaly evaluation in the period November 2006–September 2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

components (24 h, 12 h, 8 h, etc.) are observable and likely mostly linked with meteo-climatic effects. Tidal effects were not observed probably due to the smoothing role of the water gas separator device. Periodicities were removed and after normalization a residual time series was obtained (Fig. 6c and f). Due to the dependence of the residual water temperature ($T_{w\text{-}res}$) on the residual ambient temperature ($T_{a\text{-}res}$), shown by a rather high correlation coefficient ($R \sim 0.6$) (Fig. 6g), the regression line $T_{w\text{-}res\text{-}reg} = 3.10063E{-}8 + 0.56378\ T_{a\text{-}res}$ was calculated and removed from the residual water temperature, obtaining the final residual water temperature $T_{w\text{-}res2}$ (Fig. 6h), whose distribution was fitted by a Gaussian function, obtaining a $\sigma \sim 0.93$. To evaluate anomalies, which are defined as values of $T_{w\text{-}res2}$ above a fixed threshold, a 2σ threshold was assumed. The final result is presented in Fig. 6h. Fig. 7 shows the final result applied to the data set of Fig. 5 as an example.

8. Results

The statistical analysis presented requires undisturbed long term time series of recorded data. The available data set suitable for a statistical evaluation are:

- Water temperature: April 4–June 3, 2006, June 14–August 29, 2006, December 1, 2006–September 12, 2007, October 9, 2007–May 5, 2008;
- Gas flow: May to August 2007 and September 2007–February 2008;
- Water flow: February to August 2006.

8.1. Water temperature records

A comprehensive analysis of all available water temperature data is shown in Figs. 8–10. Anomalous periods above the confidence threshold of two sigma are marked by red triangles in the figures. A comparison with local seismicity is reported in Table 1. Local earthquakes are indicated by green triangles and their identification numbers.

8.2. Gas flow records

Gas flow records show typical daily variations. Anomalous gas emissions were recorded only in few periods. Figs. 11 and 12 represent the gas flow records in undisturbed periods. Only on June 23/24 and July 31–August 2, 2007, were two significant anomalies recorded.

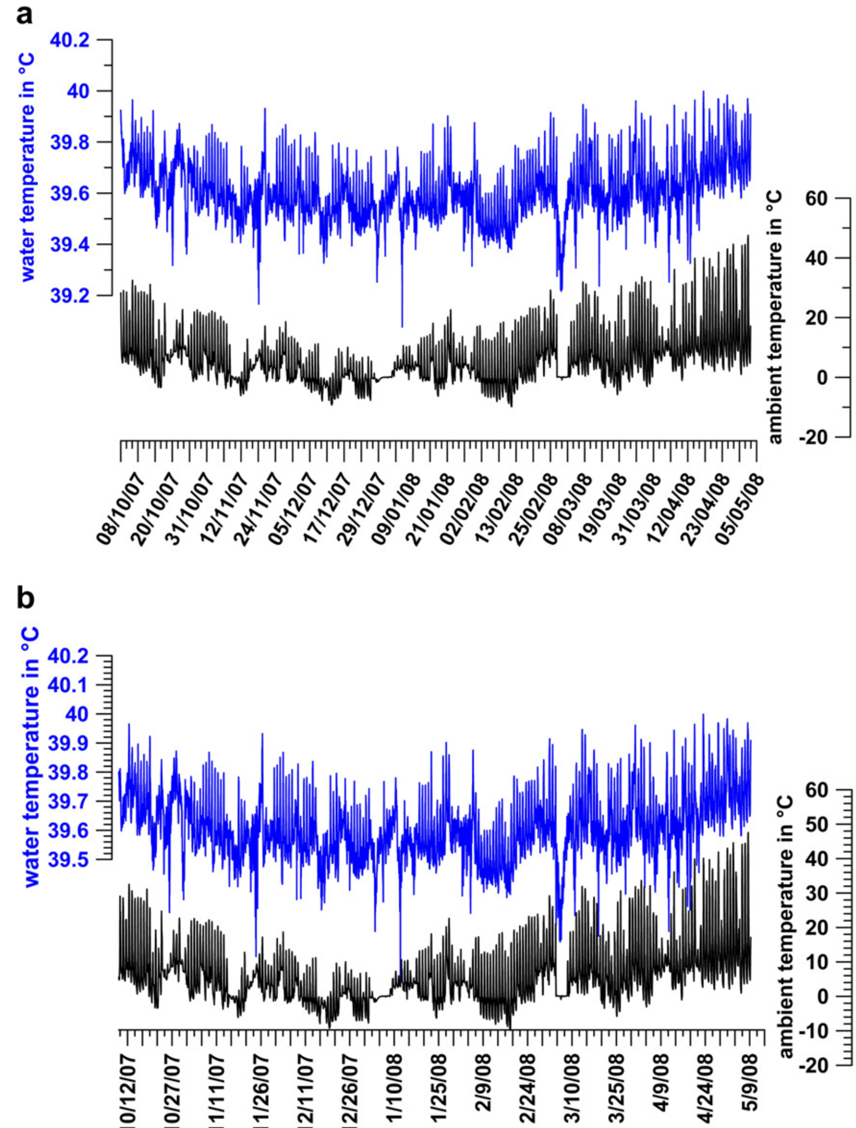

Fig. 10. Part three of the original data of water temperature (blue), ambient temperature (black) and the result of the statistical anomaly evaluation and seismicity in the period October 2007–May 2008. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

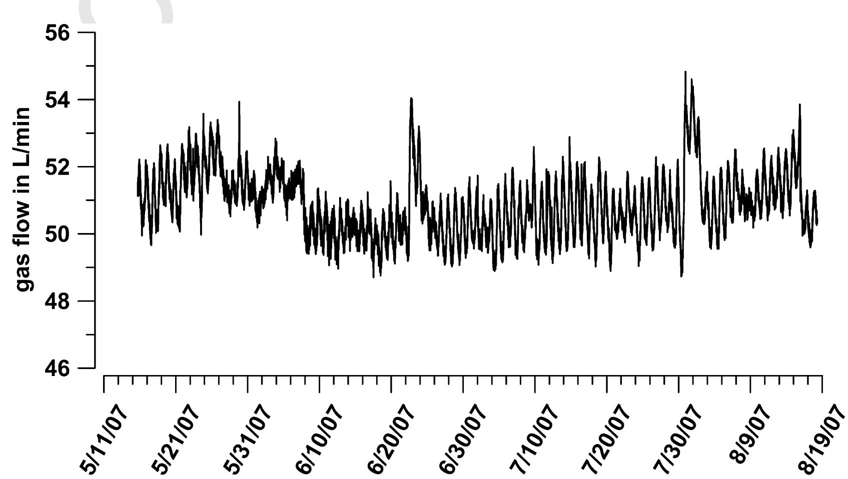

Fig. 11. Gas flow records in the period May–August 2007. Two anomalous enhanced flow rates are visible: June 23–24 and July 31–August 2.

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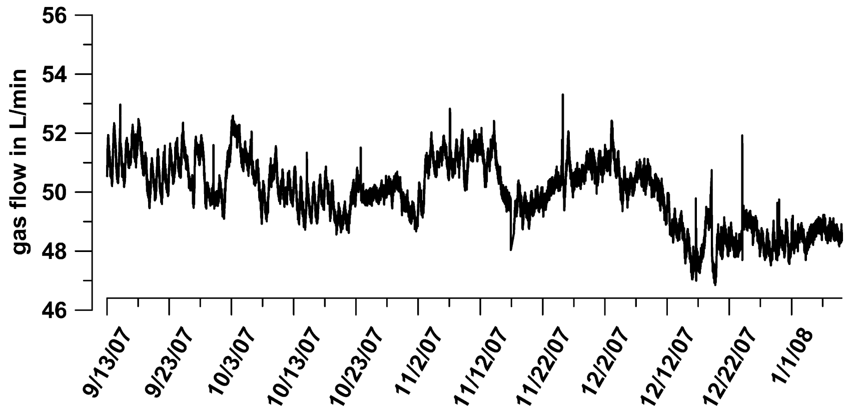

Fig. 12. Gas flow record from September 2007 to February 2008.

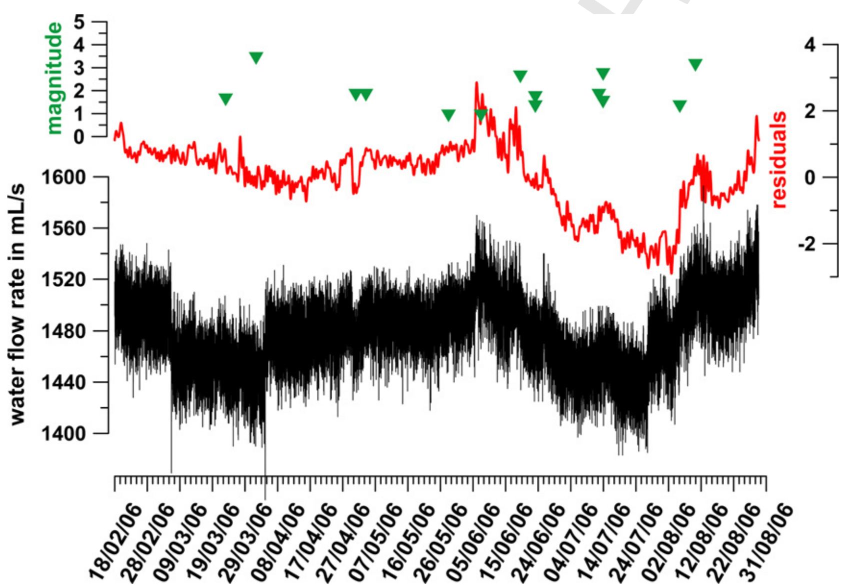

Fig. 13. Water flow record from February to the end of August 2006. The calculated residuals (red) reflect different trends in the flow rate as well as minima and maxima values. The anomalous increase at the beginning of June could be interpreted as a result of seismic events on these days (No. 33.34) but could be also part of a seismically active period occurring since April 2006 (see Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

8.3. Water flow records

The record of water flow rate is limited to the period February–August 2006. Statistical analysis by PSD and following residuals show interesting periods:

- a more or less constant period between February and June 2006;
- the increasing of flow rate on June 6, 2006;
- a peak on June 20;
- a decreasing of flow rate up to the beginning of August;
- an increase at the end of August.

9. Discussion

Fluid parameters show different variations likely induced by meteorological effects and reservoir processes. In particular ambient temperature due to sunshine effects, can be evaluated in the final result of the thermal water variations so that geogenic induced signals can be well separated. Seismicity in the studied region expresses geodynamic processes which likely influence crustal fluids such as the emission at the Miano well. Tidal effects, as typical for strain sensitive aquifers, were not detected in the time series analysis.

Variations in water discharge can be induced by stress perturbations in the reservoir. Correlation tests with local rain data and water discharge showed no indications. Fig. 13 shows water flow variations in connection with seismicity in the studied area related to seismic events listed in Table 1.

The opportunity to interpret a coincidence between single events and anomalous variations, for example on June 6 or August 6, is given but not proved. The lack of long term data sets complicates further interpretation.

Further information is obtainable from the analysis of water temperature anomalies. Several short term anomalies of water

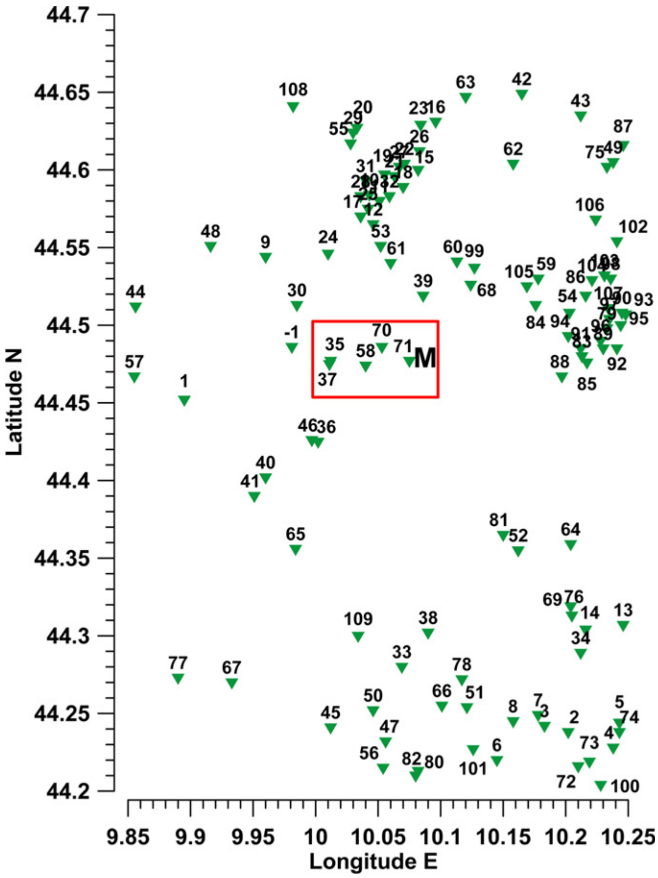

Fig. 14. Distribution of epicenters around the location Miano (M). Labels are according to labels in Figs. 8–10 and row numbers in Table 1. The red rectangle indicates the region of Fig. 17. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature were observed. Water temperature can be changed due to variations of the mixing process between different water/gas reservoirs with different temperatures, and/or variations in transport velocity. Anomaly durations lasted from 15 h up to 3 days. A comparison of these anomalies with the local seismicity could explain their occurrence.

Fig. 14 shows a geographic overview of the distribution of epicenters around the Miano well (M) listed in Table 1 within a frame of about 450 km^2.

To increase robustness of evaluation only anomalies greater than a 3σ threshold on residual time series were considered. This evaluation evidences anomalies in four periods shown in Figs. 15 and 16. In particular the comparison with seismic events close to Miano evidences:

- anomaly period of April 2006 – no seismic indication in the near field;
- anomaly period of June 16, 2006 – seismic events 35 and 37 (June 19 and 24);
- anomaly period of January 14, 2007 – seismic event 58 (February 24);
- anomaly period of June 18, 2007 – seismic events 70 and 71 (June 22 and 28).

An additional coincidence of anomalies was also recorded in June 2007. An anomaly in the gas flow was recorded 10 h after the seismic event (Fig. 18). The occurrence of a temperature anomaly on June 18–20, 2007, as a possible precursor effect of a local seismic event on June 22, followed by a post seismic gas flow anomaly on June 23/24 demonstrates that the strain process influenced both fluid reservoirs. Some hours after the shock, gas emission increased from 50 to 53 L/min. The registration of anomalies on two different parameters was observed only one time. The epicenter of seismic event No. 70 occurring on June 22 is located on the fault zone along the river Parma shown in Fig. 17. The seismogenic process characterized by a short distance between the epicenter and the borehole of around 4 km was able to influence both fluid reservoirs inducing an increase of warm water output during the stress build up and an increased gas release after the stress relaxation.

10. Conclusions

Monitoring of fluid emissions at the Miano well over 3 a has evidenced some anomalous fluid emissions probably related to local geodynamic processes. Statistical analysis of data by using the power spectra density analysis supports the anomaly detection by sigma threshold analysis. Water temperature shows the largest number of recorded anomalous variations. Many seismic events in the region occurring within a radius of about 12 km

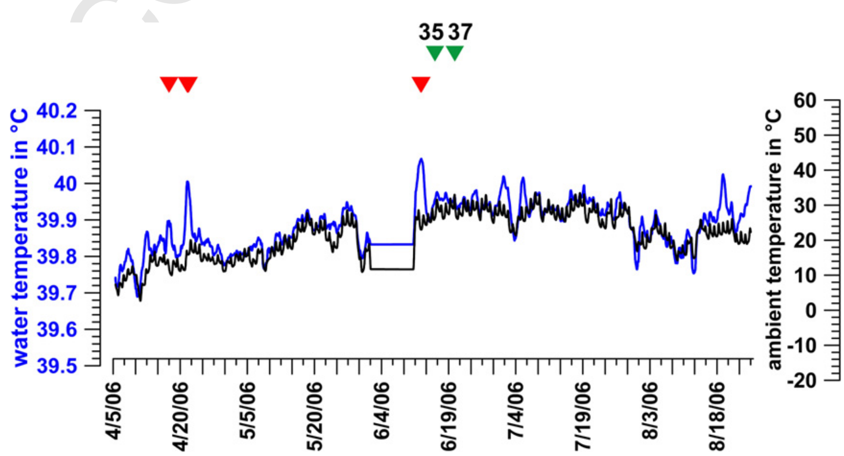

Fig. 15. Comparison of the running average temperature data (blue – water, black – ambient temperature, according to Fig. 8) with the indications of final residuals above the 3σ threshold (red) and their temporal vicinity of local events, shown also in Fig. 16. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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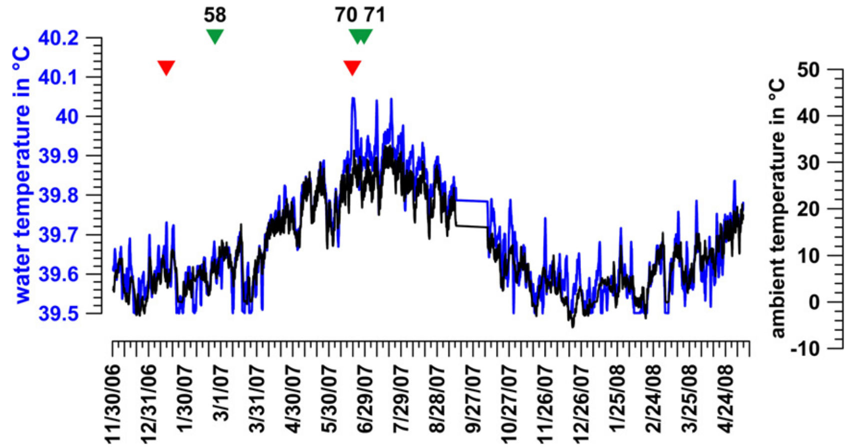

Fig. 16. Comparison of the running average temperature data (blue – water; black – ambient temperature, according Figs. 9 and 10) with the indications of final residuals above the 3σ threshold (red) and the temporal vicinity of local events shown also in Fig. 17. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

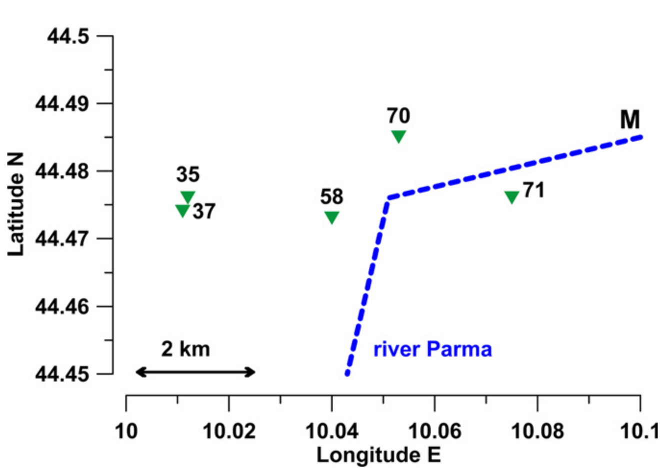

Fig. 17. Distribution of epicenters near Miano (M). The events occurred along the fault line of the Parma river. The label numbers are according to Table 1.

to the location cannot be significantly related to all of the recorded water temperature anomalies. Further analysis, using a 3σ threshold for anomaly indication and events located within 8 km SE of Miano station, revealed significant correlation between anomalous values in water temperature and narrow earthquakes. In particular some anomalous values occurred before seismic events. The fault zone indicated by the river Parma could be a preferential transport path of the pore pressure signal. Active geodynamic processes in the Northern Apennines act as a permanent force able to influence deep fluid reservoirs and fluid filled fractures. Pore pressure perturbation can induce the observed anomalies and in particular an increased output of thermal water.

Acknowledgment

One of the authors, L. Telesca, acknowledges the financial support received in the framework of the bilateral agreement CNR/DFG.

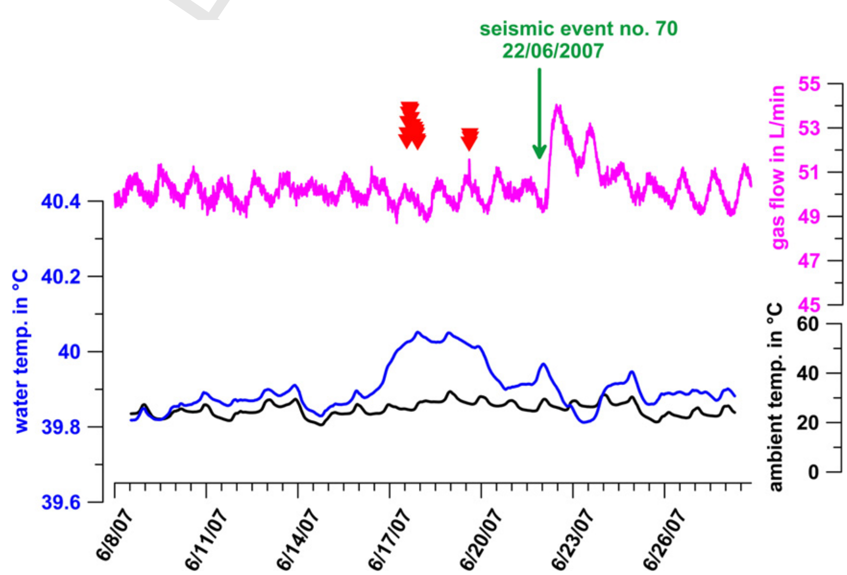

Fig. 18. Recorded anomalies in both water temperature and gas flow (pink). The comparison of the running average temperature data (blue – water; black – ambient temperature) with the indications of final residuals (red) shows an anomaly before event No. 70. After this local event the gas flow increased significantly for 2 days. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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